Development of a Commercially Successful Wearable Data Collection System

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Abstract

Symbol Technologies has completed a unique accomplishment; it has created a commercially successful Wearable Computer. The success of this product is directly due to a structured development effort. This effort took into account the varied requirements of a device worn on the human body in a heavy industrial environment. It is designed to decode bar codes and transmit the decoded information in real time to a host device via a wireless local area network. This document contains anthropometric data tables.

Figure 1. Symbol Technologies Wearable System

1. Introduction

In January of 1995, a major customer, the United Parcel Service (UPS), challenged Symbol Technologies to create a Wearable Data Collection device for their package loaders to use. Symbol already had many of the building blocks either in production or in Advanced Development. UPS's schedule and work environment was the greatest challenge to the technical development.

This system was to be Symbol's second generation wearable product intended to replace the Symbol APS 3395, which was released in 1992. The new product was required to address all aspects of the wearable system including form, fit and function of the bar code scanner, keyboard, display, terminal, cradles, batteries, charging accessories and application development tools.

Key product requirements included:

- Improved fatigue-free bar code scanner triggering.
- Size reduction of bar code scanner.
- Minimization of cables.
- Elimination of the separate CPU "brick" (PRT 3310) and second keyboard & display.
- Improved display and keyboard.
- Better "soft good" mounting garments.
- Improved hygiene.
- Intuitive, efficient battery exchange.
- Sufficient power for 5.5 hours of use.

The major technical challenges include:

- Ergonomics and hygiene - a wearable system must be safe, comfortable and as unobtrusive as possible.
- Miniaturization of the wrist mounted computer and bar code scanner.
- Power management - The customer required no less than 5.5 hours of operation on one battery. This was

over the specified temperature range of -20°C to + 50°C. Since the wrist computer had to be as small and light as possible to meet the ergonomic requirement, a power source had to found to meet these needs.

- Ruggedization - the package-loading environment is a hostile one. The product must survive repeated impacts and abrasions, as well as exposure to challenging physical conditions that include a broad temperature and humidity range, high ESD and EMI, high ambient light as well as other realities of a wearable product such as exposure to human perspiration.

2. Major technical challenges

The following sections describe in more detail the major technical challenges and the approach taken to overcome them.

2.1. Ergonomics

2.1.1. The process. The ergonomic and industrial design challenge was to integrate a high tech mobile computer/ scanning system with a comfortable soft touch wearable product. Symbol's goal for the product was to create a wearable system that increased efficiency and productivity through mobility and hands-free computing and scanning. Good ergonomics is essential for any commercially available wearable computer product. If not designed so it can be worn comfortably and safely for a ten-hour shift, the user is likely to refuse to wear the system, or use it improperly. The result would be decreased efficiency and increased safety risks.

During the first phase of product development, Symbol Technologies partnered with UPS to develop the optimum solution for the package moving industry. Symbol's product development utilizes an interactive design process that relies on user testing and feedback. UPS's key requirement was to have a conveniently located bar code scanner and computer terminal worn on users, that allowed them to be mobile and have both hands free to handle small to large packages. Symbol engineers, marketers and designers logged hours of observation and interviews with male and female users to understand their job tasks and work process. It was determined from a list of concerns that the four most important factors in the design was 1) comfort for a wide range of body sizes 2) Ruggedness 3) User safety 4) hygiene/ cleanliness.

Human Factors firms were contracted for to provide support during the entire product development process. The Human Factors experts supplied physiological data as reference material to lay the framework for designing a wearable system. Symbol used anthropometric studies of the human hand, finger and forearm from a comprehensive Air Force study (completed by Garrett, 1971 [1]). The studies underscored the importance of the neutral position for both the arm and hand. The neutral position, called the position of rest, is the position in which the resting tension of the muscles that flex and extend the fingers are in equilibrium. (Putz-Anderson, 1988 [3]). The neutral position of the wrist and arm provides both the greatest grip strength and the least work effort on the ligature of the arm and hand. (Pheasant, 1996: Tichauer, 1978 [2]). The optimum design was determined to be one where the arm, hand, and fingers assume a neutral position or near-neutral position for the majority of the operating time.

To initiate the design process, a full range of concept sketches were generated showing concepts from complete fantasy to practical. The project team then refined the concepts and picked the most innovative and practical ideas. Modelers then created mocks-ups of the chosen concepts to use as tools to determine the optimum shape and locations of the components. Industrial Designers then tested the concepts by attaching them to test-subjects' clothing in different locations with Velcro. This proved to be an efficient way to gather user feedback, collect first reactions, and discuss ideas for improving this particular approach. For example, bar code scanners were attached to various areas of the body: back of hand, chest, on a belt, on a visor and fingers. The Industrial Design team refined the models based on the test study, and then took them to UPS for the final test.

The feedback from the users at UPS was essential for the product's success in their extremely harsh environment. The designers and engineers were challenged to develop innovative ways of attaching plastic hardware to soft goods material, and soft goods material to human skin and clothing. One of the most difficult challenges was to make soft goods that were adjustable for the wide range of forearm and finger sizes for males and females. The team came up with some innovative ideas here including a simple but effective two-finger strap to hold the scanner securely on a user's finger. The soft goods also had to be designed for both left handed and right handed people. All of these factors had to be considered while balancing manufacturability, cost, and material technology constraints.

An evaluation of the potential for disease transmission associated with the use of soft goods with skin contact was performed by Dr. Richard Blume (see Acknowledgment 1.) of Sandler Occupational Medicine Associates, Melville, NY (Note: The results were published in a proprietary report to Symbol). The results of the evaluation indicated that the risks of disease transmission / communicability were minimal and essentially negligible assuming that several minor precautionary measures are followed. Nylon, Velcro, and elastic were chosen for being inorganic materials (as well as durable, absorbent, and breathable). These materials are inhospitable for living organisms. The study concluded that Symbol should recommend to the buyer that the soft goods should be the individual property of the worker for hygiene and for his perception of cleanliness.

After finalizing the hardware design and soft good approach, a laboratory based ergonomic evaluation of the wearable system was performed by Ergonomic Technologies Corporation. ("Phase 1: Ergonomic Evaluation of the Wearable System" by Ergonomic Technologies Corporation. [4]) The goal of the evaluation was to identify ergonomic and hygiene issues associated with the system in a controlled laboratory environment using predefined task simulations. A total of six subjects were used for this study (3 male, 3 female) The task simulation consisted of scanning UPS barcode labels on various size packages. The packages were stacked on a surface 29.5" above grade and the subjects were asked to scan each package and stack them on another surface 21.5" above grade and then reverse the procedure. The subjects were asked to maintain a pace between 400 and 500 scans per hour. The task simulations were approximately 2 hours in duration. Right arm forearm flexor / extensor muscle activity was recorded every half-hour during task simulation followed by comfort questionnaire regarding affected body parts. The overall comfort of the system was analyzed at the component level as well. The following aspects of the system were evaluated:

- Effectiveness of audio and visual feed back
- Activation effort for triggering the bar code scanner using one's thumb
- Keypad layout
- Ease of battery installation
- Soft good adjustibility
- RF exposure levels in relation to ANSI standards

The Wearable System was consistently rated as "Good" (4.0 on a scale of 1 to 5) for overall comfort throughout the 2-hour data collection period. The design received high marks (> 4.0 on scale of 1 to 5) for hardware configuration, keyboard layout, audio/LED feedback, cable length, battery installation, and trigger activation shape and size. Modifications were made to the design of the soft goods at this point to improve the fit and adjustability according to the results of the study. Improving the soft good design proved the most time consuming and challenging aspect of the system from an Industrial Design perspective due to the vast difference in arm and finger sizes.

2.1.2. Tables of study measurements & results

Table 1. Body part comfort ratings on a scale of 1 to 5

Comfort	Statistic	Trial 1	Trial 2	Trial 3
Hands & Finger Comfort	Average	4.46	4.05	3.83
	Std. Dev.	0.46	0.24	0.41
Wrist Comfort	Average	4.54	4.08	4.08
	Std. Dev.	0.51	0.20	0.20
Forearm Comfort	Average	4.04	3.70	3.67
	Std. Dev.	0.64	0.55	0.52
Shoulder Comfort	Average	4.13	4.03	4.00
	Std. Dev.	0.67	0.08	0.01
Neck/Upper Back Comfort	Average	4.29	3.93	4.00
	Std. Dev.	0.75	0.49	0.01
Lower Back Comfort	Average	4.46	3.75	3.83
	Std. Dev.	0.46	0.61	0.41
Overall Comfort	Average	4.04	4.00	4.00
	Std. Dev.	0.10	0.00	0.10

Table 2. Design evaluation ratings

Scanner Feature	Average	Std. Dev.
Comfort of Ring Component	3.92	0.67
Size of Ring Component	3.50	1.00
Shape & Contours of Ring Component	4.17	0.68
Overall Fit of Ring Component	3.60	1.20
Comfort of Forearm Component	3.70	0.60

Scanner Feature	Average	Std. Dev.
Size of Forearm Component	3.80	0.40
Shape & Contour of Forearm Component	3.90	0.20
Overall Fit of Forearm Component	3.60	0.90
Overall Weight of System	3.90	0.50
Ring Component Mounting Method	4.00	1.05
Forearm Component Mounting Method	3.92	1.20
Fit of Mounting Sleeve	3.42	0.66
Breathability of Mounting Sleeve	3.83	0.41
Position of Light Indicator	4.17	0.26
Audible Feedback of System	4.13	0.65
Usability of Keypad	4.08	0.20
Spacing between Keys on Keypad	4.17	0.26
Legibility of Keys on Keypad	4.42	0.49
Visibility of Keys on Keypad	4.50	0.55
Legibility of Display	4.33	0.41
Illumination Of Level of Display	4.42	0.49
Ease of Battery Installation	4.42	0.49
Cable Length (Ring to Forearm Component)	4.17	0.98
Location of Trigger	4.33	1.03
Trigger Activation Effort	4.17	1.13
Shape & Size of Trigger	4.25	1.17
Overall System Rating	3.92	0.66

Table 3. Male subject characteristics (Symbol test)

Measure	Avg.	Std. Deviation	Max.	Min.
Age (years)	27.33	2.52	30	25
Grip Force (pounds)	118.80	11.64	132	110
Height (inches)	70.67	1.53	72	69
Weight (lb.)	182.30	20.40	200	160
Wrist Circumference (inches)	6.79	0.19	7	6.63
Forearm Circumference (inches)	11.46	0.51	12	11
Index Finger Circumference (inches)	2.75	0	2.75	2.75
Index Finger Length (inches)	2.96	0.07	3	2.88
Forearm Length (inches)	10.79	0.26	11	10.5
Hand Length	7.58	0.38	8	7.25
Hand Breadth Metacarpal (inches)	3.79	0.32	4.13	3.50
Hand Breadth w/Thumb (inches)	4.17	0.07	4.25	4.13

Table 4. Female Subject characteristics

Measure	Avg.	Std. Deviation	Max.	Min.
Age (years)	25.67	3.22	28	22
Grip Force (pounds)	59.33	1.16	60	58
Height (inches)	67.17	0.76	68	66.50
Weight (lb.)	135	10	145	125
Wrist Circumference (inches)	5.83	0.29	6	5.5
Forearm Circumference (inches)	9.25	0.75	10	8.5
Index Finger Circumference (inches)	2.5	0	2.5	2.5
Index Finger Length (inches)	2.79	0.07	2.88	2.75
Forearm Length (inches)	9.50	0.76	10	8.63
Hand Length (inches)	7	0.13	7.13	6.88
Hand Breadth Metacarpal (inches)	3.28	0.13	3.38	3.13
Hand Breadth w/Thumb (inches)	3.5	0	3.5	3.5

2.2. Miniaturization

A major constraint to creating an ergonomic wearable product design is product package size. In order to make a small, lightweight product, its sub-systems must be miniaturized as much as possible.

Leading edge printed circuit board construction and assembly technology was employed. A Symbol designed bar code scanner motor control ASIC (Application Specific Integrated Circuit) was employed and mounted as bare die using Chip on Board (COB) methodology. An "off-the-shelf" OPAMP package from Texas Instruments was COB mounted as well to save space. The raw PCB used a "rigged flex" design to eliminate the need for on board connectors and interconnecting flex strips.

2.3. Power management

One of the most significant challenges facing the team was to design a power system that was small, light, and could power a DOS computer with a laser-based bar code scanner and 900MHz radio for 5 ½ hours at 0°C and for 1 hour at (-20°C). The usual Nickel Cadmium and Nickel Metal Hydride battery cells were too heavy and too large. Lithium ion (Li-ion) batteries seemed the answer to this dilemma, but the technology wasn't quite mature enough.

A cylindrical type 18650 Li-ion cell with 1280Mah of capacity was chosen as the only viable power source for this lightweight computer. Symbol worked closely with the battery cell manufacturer as we together revealed some of the issues with this relatively new technology.

Due to the volatility of the new battery technology, we decided to include a protection circuit inside the battery pack in case of a short or over-voltage condition. This circuit required many iterations to solve problems in disconnecting battery voltage and controlling the impedance of the battery pack.

Another characteristic of Li-ion cells that complicated the design of power management was the high internal impedance of Li-ion cells. The wearable computer had large peaks of current in excess of 2A that dropped battery voltage dramatically for a few microseconds at a time. This problem was exaggerated at the cold operating temperatures that the unit had to operate at (-20°C). The large voltage drops caused the unit to shut off well before all battery capacity was exhausted. New analog circuits combined with many iterations of power-management software were required to use all of the battery capacity and have the unit operate reliably. In the end, we were able to get close to 7 hours of battery life at 0°C exceeding our customer's requirement.

2.4. Ruggedization

2.4.1. Symbol RS-1™ "Ring" Scanner. The Opto-mechanical system of the "Ring" bar code scanner is based upon a dust proof design concept. Conventional means for sealing the unit were used as well as special design features: 1) a labyrinth designed around the sides of the exit window, 2) reinforcement by application of silicone sealant, 3) the use of a closed-cell foam gasket.

The LED indicator window was designed with an enlarged inner flange for additional protection against dust penetration and Electro-Static Discharge (ESD). The electrical connector on the back of the bar code scanner utilizes a soft plastic over-mold to provide sealing at the connector/housing junction.

The upper housing of the bar code scanner has an additional seal plate to provide a labyrinth around mounting screw gaps.

See Figure 2 for the decode performance of the Symbol RS-1™ "Ring" Scanner.

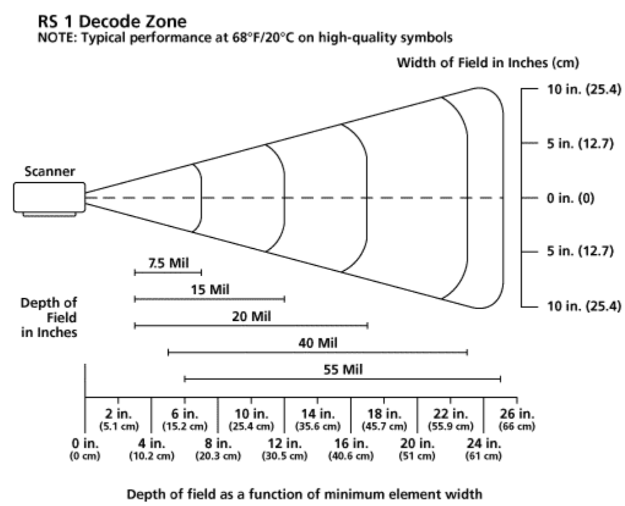

Figure 2. Bar Code Scanner Decode Zone

2.4.2. Symbol WWC 1000™ Wrist Computer. The Wrist Computer was designed using an internal wrap-around mylar part that serves as an ESD shield while allowing RF radiation to be emitted from the unit.

The top cover of the Wrist Computer has substantial dust protection features as well as shock insulation which combines with an external rubber boot to provide significant drop and abrasion protection.

A strain relieving coupler is molded around the interface cable. This feature is designed to allow the cable to be swiveled for either Left or Right hand operation while also providing dust sealing.

3. Implementation details

3.1. Leveraged design elements

The building blocks for the system included:

- An index figure mounted laser based bar code “ring” scanner which was already being developed and leveraged its analog and optical architecture from Symbol’s SE-1000™ scan engine.
- Symbol’s 16 bit handheld computer here based off the Symbol PDT-3100™.
- Symbol’s spread spectrum (902-918MHz) wireless LAN, called Spectrum I ™.

3.2. System block diagram

The wearable scanning system consists of three major parts: 1) the ring bar code scanner, 2) wearable computer and 3) cradle. Each major part consists of subsystems as shown below. The CPU subsystem is the heart of the entire system and is based on an NEC V25 “computer on a chip” running DOS. An ASIC in the subsystem controls data acquisition by the bar code scanner, memory mapping, radio communication, and other I/O functions. To program the wearable computer, an IR link connects the system to a cradle that allows RS232 communication to a host. The cradle also provides quick charging of the unit’s battery including spare in less than two hours.

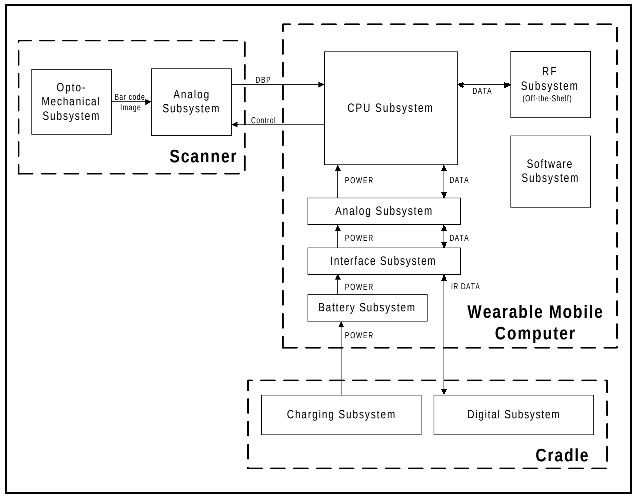

Figure 3. System block diagram

4. Refinements resulting from user testing

The prototype resulting from the concept and initial implementation phase was subjected to over 40,000 hours of user testing in UPS hubs. The tests were conducted utilizing 120 to 240 truck loaders per shift. The tests took place over several months with shifts typically lasting four to five hours. Naturally, a great deal of learning took place since this was the first wearable computing field test of this magnitude. The most significant findings concerned the wearable aspects of the system as opposed to bar code scanning, computing, electronics, and software, which are well understood technologies.

The ring scanner attachment device, which is referred to as the ring carrier, required contour modifications to eliminate user discomfort and injury. There were also provisions added to direct sweat away from sensitive areas of the system. The force required to break the ring carrier away from the user was difficult to define because a force too great would compromise user safety while a force too small would allow too-frequent separation in this rough environment. A force was eventually agreed upon that would protect the smallest of users from injury. The breakaway force for the wrist computer from the wrist computer attachment device, and from the wrist computer to the ring bar code scanner presented a similar challenge.

An unexpected challenge resulted from the required partnership between too very different industries: high-tech and clothing. The fastening devices included various cloth solutions and snaps, therefore, a partnership with clothing suppliers was needed. Although tight dimension tolerances were truly needed for the attachment devices to work properly, this level of detail was unfamiliar to the clothing suppliers. There were two attachment device design constraints that were very challenging: they had to support ambidextrous use and they could only be provided in one size to fit all. The soft goods went through at least ten trial periods where the fit and comfort were evaluated and refined based on user feedback. Sometimes a new change would be no better or even worse than the last change.

The extreme ruggedness needed for the UPS environment was underestimated in initial design and testing. After several months of use in the UPS environment the abrasion from the corrugated boxes had worn holes in the top of the zinc cast ring from repeatedly plunging both hands between stacks of boxes. To alleviate this, additional protective boots were added. These low-cost-consumable devices absorb impact and abrasion providing a cost-effective solution that effectively protects the customer's hardware investment and reduces the amount of failures. The protective boot for the wrist computer was permanently attached to the wrist attachment to ensure that it was used. This type of mistake proofing is important since it's impossible to ensure proper training and discipline among 40,000 users in nearly 300 hubs across the country.

5. Conclusion

The final product, the Symbol WSS 1000 Wearable Scanning System, which includes the Symbol RS-1™ "Ring" bar code scanner and Symbol WWC 1000™ Wrist Computer, was released in September of 1996 with 17,000 units being shipped to UPS that month. To date, over 30,000 units have been shipped to customers in various industries including Parcel Tracking, Transportation and Logistics, Grocery Distribution and Retail Distribution.

Users of the new wearable system applaud its usefulness in allowing them to be more productive in their day to day jobs. The system is used primarily in warehouse applications where users are moving inventory manually and need both hands free. Companies study the effectiveness and have found the system to be more productive in applications where users need their hands free. The initial response from users who had been using hand-held computers was to not want to give up the wearable once they tried it. Customers reported incidents where users were coming in early for work just so they would get a chance to use the wearable system. The wearable is always chosen in handling intensive applications where it is tested against hand-held computers, and this attests to the validity of the wearable concept.

As was the case during initial development, the product is still evolving. Recently, Symbol Technologies added its Spectrum 24™ 2.4 GHz Spread Spectrum IEEE 802.11 compliant wireless LAN to the system. In addition, the scanner and wrist attachments continually are being updated based on end user input.

Developing a laser barcode scanner to fit on a user's finger and a DOS wireless LAN computer on a user's wrist were significant achievements for Symbol and the data collection industry. Looking to the future, Symbol is researching technologies that will allow even smaller wearable computer systems. Voice recognition, local body area networks, and new display technologies are being explored along with a new scanner that promises to shake up the industry once again.

6. Acknowledgements

1. Dr. Richard Blume is a board certified specialist in occupational medicine. He serves as an occupational health consultant to a wide range of industries and provides guidance and recommendations for development of safety and health programs, including programs for the prevention of disease transmission in the workspace. He has published and made scientific presentations on numerous subjects pertaining to occupational and environmental health.

7. References

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